HISTORY OF STAR FORMATION RATE AND LUMINOSITY DENSITY OF GALAXIES

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ABSTRACT

We have computed the time evolution of bolometric, far-infrared, Hα line, ultraviolet (both intrinsic and escaping the star forming region) and the nonthermal radio continuum luminosities for continuous and constant star formation terminating at 95 Myr. The luminosity rises to a plateau value and declines after the termination of starburst, but only gradually. The time evolution profiles are broad and different for different star formation indicators. The broad profiles lead to uncertainties in the star formation rate derived depending on the initial mass function, duration of starburst, its distribution and the observational epoch.

INTRODUCTION

In recent years there have been several studies of the cosmological history of star formation rate (SFR) in galaxies. Usually the SFR is derived from the luminosity density in a selected wavelength band which is an indicator of star formation. Some of the SF indicators that have been used are: Hα line, far-infrared (FIR), submm, ultraviolet (UV) and nonthermal radio continuum emissions. Each indicator is sensitive to a certain range of stellar masses and the total SFR is obtained by assuming an initial mass function (IMF) of stars at birth, usually a power-law form. Further, the observed luminosity depends on the star formation history and the epoch of observation. Even for a constant rate of star formation, there is a time evolution of luminosity which increases, reaches an equilibrium value and declines after the termination of SF. This evolution and decline also depend on the exponent of the IMF. The changes in the luminosity to SFR ratio as a function of these parameters are not the same for all indicators. Thus, apart from the observational errors, uncertainties arise in the SFR derived from luminosity density using different indicators. In this paper, we study these uncertainties by computing the evolution of the luminosity to SFR ratio for different IMFs and scenarios of star formation. It should be noted that there are other parameters like metallicity that can affect the derivation of SFR from luminosity. For example, Hirashita et al (2001) find that the FIR-SFR conversion factor can vary by a factor of up to 4 on this account. When we have better knowledge of factors like metallicity and cirrus contribution in starburst galaxies, it may be possible to quantify these uncertainties.

COMPUTATION

In this study we compute the time evolution of L/SFR ratio for the following luminosities: L_{bol}, the bolometric luminosity, L_{fir}, the far-infrared luminosity which is a fraction of the bolometric luminosity, L_{uvi}, the intrinsic luminosity in an ultraviolet band, L_{uve}, the luminosity of uv photons escaping the star forming region, L_H, the Hα line luminosity and L_R, the nonthermal radio continuum luminosity. For UV we use the 0.16 μm band which has been extensively used in HST observations. The submm luminosity is usually converted into a FIR luminosity to derive the SFR and hence we do not consider it separately. The radio continuum is assumed to be from synchrotron emission from cosmic ray electrons accelerated by supernovae arising from stars of mass > 8 $M_\odot$. In starburst(SB) galaxies, which are the subjects of our study, the contribution of the earlier disc population is small and is neglected. Their contribution, if present,

will add additional uncertainties. The FIR luminosity is dust-reradiated emission and in many studies, it has been taken to be the same as the bolometric luminosity. Though this is likely to be the case at the very early embedded stage of a star, the efficiency of conversion will be less than unity and decrease as time passes because of the disruption and dispersion of the parent clouds by the massive stars formed. The fact that visible OB stars are observed in star forming complexes in the Milky Way supports this hypothesis. Silva et al. (1998) have introduced the concept of residence time and have shown that their models give good fits to observational spectral energy distributions and spectral line data. In this study, we assume that the FIR conversion efficiency decreases exponentially with a time constant τ. It then follows that the flux of UV photons escaping the star forming region depends inversely on this conversion efficiency and can be characterized by an extinction which decreases exponentially with the same time constant. The Hα luminosity will also have a similar dependence with a proper scaling of the extinction.

The total luminosity in a given band is the integral over the history of stellar formation and evolution and over the stellar masses. The IMF is assumed to have a power law form $\xi(\mathrm{m}) \propto \mathrm{m}^{-\gamma}$ within mass limits of 120 to 1 $M_\odot$. Since the contribution of stars of mass < 1 $M_\odot$ to the luminosity, in the bands considered, is negligible, the L/SFR ratio can easily be scaled for an IMF extending to lower masses. The stellar evolutionary tracks are taken from Schaller et al. (1992) and the computational procedure follows that of Mayya (1995). The integrated luminosity at time T, the epoch of observation is given by

$$L_{bol}(T) = \int_1^{120} \xi(m)dm \int_T^0 p(t) L_{bol}(t,m) dt \tag{1}$$

$$L_{fir}(T) = \int_1^{120} \xi(m)dm \int_T^0 p(t) L_{bol}(t,m) e^{-t/\tau} dt \tag{2}$$

$$L_{uvi}(T) = \int_1^{120} \xi(m)dm \int_T^0 p(t) L_{uv}(t,m) dt \tag{3}$$

$$L_{uve}(T) = \int_1^{120} \xi(m)dm \int_T^0 p(t) L_{uv}(t,m) 10^{-0.4A(uv)exp(-t/\tau)} dt \tag{4}$$

$$L_H(T) = K_H \int_1^{120} \xi(m)dm \int_T^0 p(t) L_{Lyc}(t,m) 10^{-0.4A(H)exp(-t/\tau)} dt \tag{5}$$

$$L_R(T) = K_R \int_8^{120} \xi(m)dm \int_T^{Min(T,t^*(m))} p(t) e^{-t/\tau_e} dt \tag{6}$$

Here t is the look back time when a star is born, T is the observational epoch from a reference time when the starburst started, p(t) is the production rate of stars at time t, t*(m) is the lifetime of a star of mass m, A(uv) and A(H) are the extinctions in magnitudes at 0.16 μm and Hα wavelength at the time of birth, Lyc refers to Lyman continuum photons and K_H is a constant that relates Hα luminosity to the Lyman continuum luminosity and K_R is the nonthermal radio continuum luminosity per supernova and τ_e is the exponential residence time of synchrotron emitting electrons. The production term p(t) represents the time evolution of the starburst. It is a δ function for an instantaneous burst, constant for a continuous and constant star formation and could have other forms like an exponential decay or a gaussian.

The IMF index is neither known accurately nor is it known to be universal. Observations of stellar clusters in the Milky Way and the Magellanic clouds give a range of 2 to 3 (Scalo 1998). We, therefore, perform computations for three values of γ = 2, 2.5 and 3. As for the time dependence of star formation, we will consider, in this paper, only the case of p(t) = constant for t = 0 to T_B and zero elsewhere and present the results for T_B = 95 Myr. As for the residence time of stars in the parent clouds, Silva et al. (1998) find that for the starburst galaxies they model, a value of 10–20 Myr fits the observations. Here, we take τ = 15 Myr. The extinction at 0.16 μm and Hα are taken as 10 and 3 magnitudes respectively. The UV extinction adopted leads to a luminosity weighted extinction factor of 5-6 at times $>$ 50 Myr similar to the value estimated by Steidel et al. (1999). It may be noted that for moderately obscured regions, a more elaborate attenuation model is needed. However, for the luminous starburst galaxies, especially at moderate and large redshifts, our treatment may be adequate. As remarked earlier the presence of older star-forming regions will add further uncertainty to the SFR. For the residence time of high energy electrons, we take τ_e = 10 Myr.

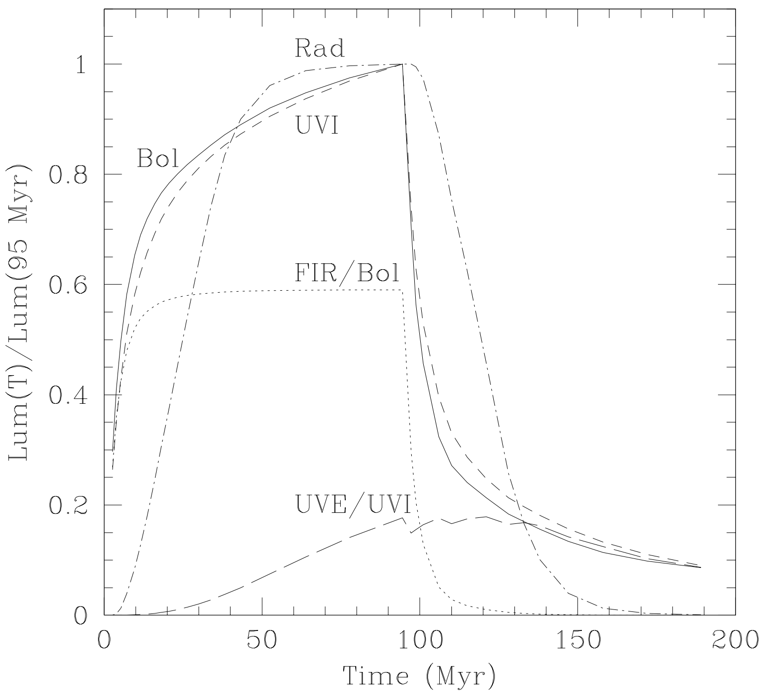

Fig. 1. Time evolution of luminosities for a continuous and constant star formation and IMF index $\gamma = 2.5$. For FIR and UVE, escaping uv luminosity, ratio with respect to bolometric and intrinsic uv luminosity respectively are shown with the same numerical scale.

RESULTS AND DISCUSSION

In Figure 1, we show for different SF indicators, the time evolution of the ratio of luminosity at time T to that at 95 Myr when the SB terminates. We have not shown the curve for Hα since it is very similar to that of the FIR. For FIR and UVE, we show the ratio with respect to the bolometric and intrinsic uv luminosity respectively. The general trend of the time evolution is an increase of the luminosity to a plateau value and then a decrease after the SB terminates.The plateau values of the ratio of luminosity to SFR for the bolometric, FIR and uv (0.16 μm)emissions are 1.6×10^{10} $L_\odot {M_\odot}^{-1}$ Yr, 8.8×10^{9} $L_\odot {M_\odot}^{-1}$ Yr and 5.5×10^{20} W Hz^{-1} ${M_\odot}^{-1}$ Yr respectively. These values, after adjustment for the Salpeter IMF and the 0.1–100 $M_\odot$ range adopted by Kennicutt (1998),are about the same as those given in his review. Further, the ratio of FIR to radio continuum fluxes is similar to that of Bressan et al (2002) if we adopt their value of nonthermal emission per supernova.

The rise- and fall-times vary from band to band. The time profile for the FIR luminosity is the sharpest while it is the broadest for the UVE. This is due to the fact that luminous massive stars have lifetimes $<<$ the residence time and almost the total bolometric luminosity is re-radiated in the FIR while for stars with lifetime $>$ 15 Myr, the conversion efficiency decreases. The opposite is the case for the escaping uv photons. For τ = 15 Myr, the maximum conversion efficiency is 0.55. It will be lower if τ is less. The fraction of escaping uv photons reaches a maximum of 0.17. The uv extinction is more sensitive to the values of τ and extinction at zero age than the FIR conversion efficiency. The slight increase in the UVE luminosity after the termination of the SB and the subsequent oscillation is due to a competition between the death of massive stars and increased escape of uv photons from lower mass stars as the stars age. It may be noted that the FIR profile is sharper than that of the bolometric luminosity while the UVE approaches that of UVI in the post starburst period. The radio continuum luminosity has a rise- and fall-time of about 30 Myr, the lifetime of stars of mass 8 $M_\odot$. The plateau FIR and UVE luminosities depend on τ, the residence time. Hence, there will be additional uncertainties in the SFR resulting from the variation of τ from galaxy to galaxy and its possible dependence on the intensity of starburst. It is generally believed that the FIR emission is least subject to extinction correction applicable to other wavelengths. However, the concept of

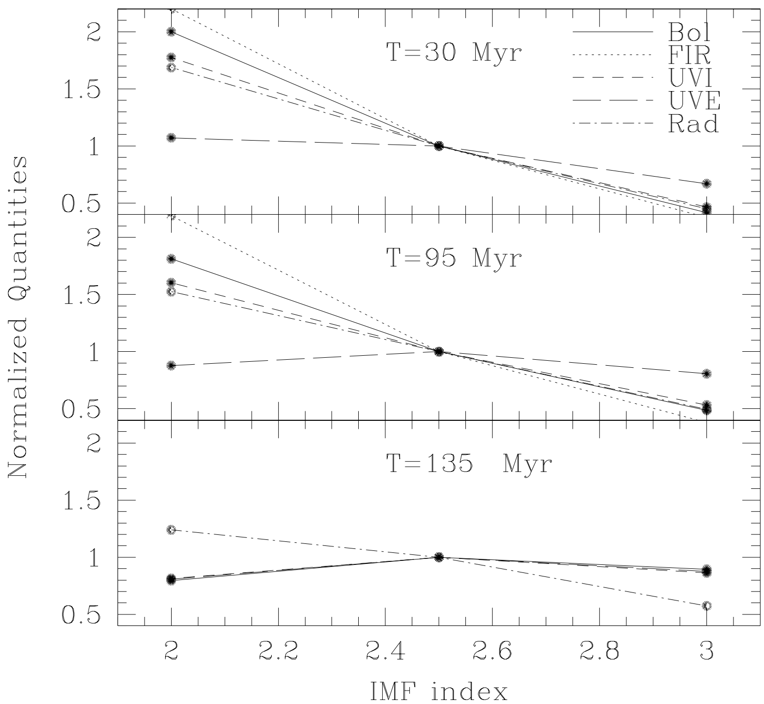

Fig. 2. Luminosity to SFR ratio normalised to the value for IMF index $\gamma =$ 2.5 plotted against γ for three observational epochs. The points are joined together to facilitate viewing.

residence time introduces corrections up to a factor of 2–3. From this point of view, the radio continuum emission is a better probe of SFR since it needs no such correction.

It is clear that the SFR derived for an individual galaxy depends on the duration of the SB and the time of observation and the luminosity does not give the instantaneous current SFR unless one observes in the plateau region of continuous and constant star formation. Even if we observe a large enough sample of galaxies, say in a given redshift bin, and all galaxies have the same duration of starburst and other parameters remain the same, the uncertainty is not fully eliminated. If we assume that the SB duration is the same for all galaxies, at any given time one will observe galaxies distributed uniformly over the evolutionary stage. Though the plateau luminosity may be higher than the observational threshold, in the rising portion of the evolutionary curve, galaxies will be missed when the luminosity is below the threshold. In the post starburst period, one will observe galaxies above the threshold though there is no ongoing star formation. For example, if the luminosity is n times the observational threshold and t_1 and t_2 are the times when the fraction of plateau luminosity is 1/n in the rising and falling stages respectively (see Fig. 1), the fraction of galaxies that will be missed is t_1/T_B and the additional contribution from the post SB period is $(t_2\text{-}T_B)/T_B$. The effect depends on the SF indicator used, the duration of the SB and the luminosity function in the chosen band. The FIR emission is a good tracer of 'instantaneous' SFR since both the rise and fall are steep. For the radio continuum, there is a net over-estimation since the decline in the post SB period is slower. Using the 1.4 GHz radio luminosity function of Haarsma et al (2000) for convolution and data of Fig.1, we find the net over-estimation of the luminosity density to be 26 %. The over-estimation in the case of uv photons is much higher. The corrections also depend on the duration of the SB. For low values of SB duration, the plateau region is a small fraction of the total and hence the correction is more. Thus, the uncertainties are significant as long as the SB duration is $<$ 150-200 Myr.

Effect of IMF Variation

In Figure 2 we have plotted, the luminosity to SFR ratio normalized to the value for the IMF index γ = 2.5 vs γ for three epochs, 30 Myr, 95 Myr and 135 Myr. It is seen that the variation with index is not the same for the different bands. The FIR luminosity shows the maximum variation, a factor of more than 5 as the index changes from 2 to 3. The escaping uv photons show the least change. Further, the changes

also depend on the observational epoch. Thus, for individual galaxies, one can have large uncertainties in SFR if the IMF varies. If a large sample of galaxies is available, the average over varying index will result in reduced uncertainty.

It is not known whether the IMF extends from high mass to low mass stars in the same region at the same time. In intense starbursts it is believed that the IMF is biased towards high mass stars. In the Galactic star forming region W3, Megeath et al (1996) find that on extrapolation of the observed IMF for $M < 10\ M_\odot$, they expect to see only one star of mass $> 10\ M_\odot$, but radio continuum observations show the presence of six high mass stars. If in starbursts, the IMF does not extend below, say $10\ M_\odot$, the luminosity computed would not change much, but the total stellar mass would be lower. If IMF bias is present and varies from galaxy to galaxy, there will be additional uncertainties in the derived SFR.

SUMMARY

We have computed the time evolution of luminosity in different bands of star formation indicators for the case of a continuous and constant star formation. The luminosity rises from the time the starburst begins, reaches a plateau value and declines after the termination of the starburst. The post-burst decline is generally, slower than the growth at early times. We have adopted the concept of residence time to calculate the FIR and escaping uv luminosities. The FIR luminosity has the sharpest profile while the uv luminosity has the broadest. The star formation rate derived from luminosity density is subject to uncertainties depending on the shape of the IMF, the residence time parameter, the duration and distribution of starburst and the observational epoch.

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